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Measurement of rates of jets produced in association with W and Z bosons with the CMS detector

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We present several measurements of vector boson production in association with jets in pp collisions at 7 TeV center-of-mass energy at the LHC, based on 36 pb^{-1} of data recorded by the CMS detector in 2010. We discuss results for the normalized inclusive rates of jets $\sigma(\mathrm{V}+\geq n\ \mathrm{jets})/\sigma(\mathrm{V})$, where V represents either a W or a Z; the ratio of W to Z cross sections; and a test of Berends–Giele scaling. In addition, we present studies of the production of vector bosons in association with heavy quark (b, c) jets which provide information on the b-quark and s-quark densities in the proton at LHC energies. Furthermore, we discuss a first measurement of the polarization of W bosons with large transverse momenta in pp collisions, where the W boson recoils against several energetic jets.

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The four analyses on vector boson production in association with jets [1, 2, 3, 4] discussed in the following are based on 36 pb^{-1} of data taken with the CMS detector at the LHC in 2010. A detailed description of the CMS detector can be found in [5].

1. Jet production rates in association with W and Z bosons

The study of jet production in association with a W or Z vector boson (in the following generically refered to as V) provides a stringent test of perturbative QCD calculations. The presence of a vector boson provides a clear signature of the process and allows comparison of different scattering amplitudes with respect to inclusive multijet production, which is dominated by gluon scattering. In addition, a precise measurement of the W (Z) + n jets cross section is essential since the production of vector bosons with jets constitutes a background in searches for new physics and for studies of the top quark. At present, next-to-leading-order (NLO) predictions are available for V + n jets, with n up to four [1].

Signal selection begins with the identification of a charged lepton, either an electron or a muon, with $P_T > 20$ GeV. Jets are reconstructed with the anti-k_T clustering algorithm with a size parameter of $R = 0.5$. Jet energy corrections are applied to account for the jet energy response as a function of η and E_T. We require the jet to have $|\eta| < 2.4$ to be in the tracker acceptance, and $E_T > 30$ GeV, to minimize the effect of pile-up. The signal yield is estimated by means of an extended maximum-likelihood fit to the dilepton invariant mass distribution for the Z + jets sample, and to the transverse mass distribution for the W + jets sample. The probability distribution functions are asymmetric Gaussians with tails. Their parameters are derived from the simulation or, for the background, from control data samples with inverted identification (isolation) requirement on the electrons (muons). In order to estimate the scaling behaviour of the jets at the particle-jet level, we apply an unfolding procedure that removes the effects of jet energy resolution and reconstruction efficiency.

Results are given for the leptons within the acceptance defined by the kinematical selection cuts in the electron (muon) channels: leading-lepton $P_T > 20$ GeV and $|\eta| < 2.5$ (2.1); second-lepton $P_T > 10$ GeV and $|\eta| < 2.5$ (2.4). In addition, electrons in the $1.4442 < |\eta| < 1.566$ region are excluded, and jets are not counted if $\Delta R < 0.3$ with respect to an electron from the W or the Z. Since the acceptance is different, we do not combine the results for the electron and muon channels.

Two sets of ratios from the unfolded jet multiplicity distributions are calculated. The first set of ratios is $\sigma(\mathrm{V}+ \geq n \text{ jets})/\sigma(\mathrm{V})$, where $\sigma(\mathrm{V})$ is the inclusive cross section, and is presented in the upper frames of Fig. 1. The second set of ratios is $\sigma(\mathrm{V}+ \geq n \text{ jets})/\sigma(\mathrm{V}+ \geq (n-1) \text{ jets})$, shown in the lower frames of Fig. 1. The contributions of the systematic uncertainties associated with the jet energy scale (including pile-up effects) and the unfolding are shown as error bands in the figures.

All results are in agreement with the predictions of the MADGRAPH generator, using matrix-element calculations for final states with jets, matched with PYTHIA parton shower. In contrast, the simulation based on parton showers alone fails to describe the jet rates for more than one jet.

Finally, we test for Berends–Giele scaling [1] and measure its parameters. Events are assigned to exclusive jet multiplicity bins (inclusive for $n \geq 4$), and the corrected yields are fitted with the assumption that they conform to a scaling function: $C_n \equiv \sigma_n/\sigma_{n+1} = \alpha$, where $\sigma_n = \sigma(\mathrm{V}+ \geq n \text{ jets})$, and α is a constant. We find that this relationship works well up to the production of four

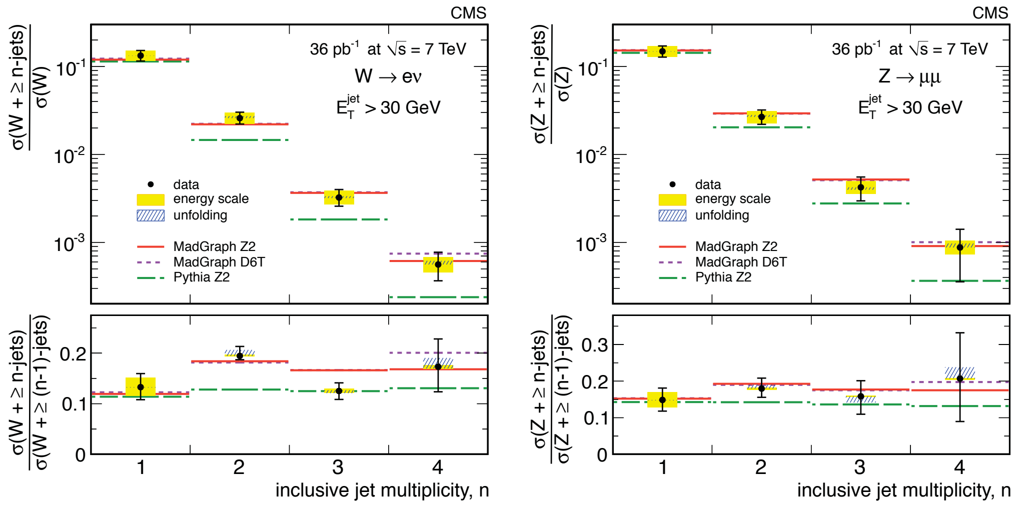

Figure 1: The ratios $\sigma(\mathrm{V}+\geq n \text{ jets})/\sigma(V)$ (top) and $\sigma(\mathrm{V}+\geq n \text{ jets})/\sigma(\mathrm{V}+\geq (n-1) \text{ jets})$ (bottom) for W production in the electron channel (left) and for Z production in the muon channel (right), compared with the expectations from two MADGRAPH tunes and PYTHIA. Points with error bars correspond to the data. The uncertainties due to the energy scale and unfolding procedure are shown as yellow and hatched bands, respectively. The error bars represent the total uncertainty.

jets. The β parameter lies within one standard deviation from zero for the W + jets case and within 0.5 standard deviations for the Z + jets case.

2. Measurement of polarization in boosted W decays

In the production at the LHC of W bosons with large transverse momenta recoiling against several energetic jets, the nature of the initial state leads to an enhancement of the quark-gluon contribution to V + jets production when compared to the Tevatron $p\bar{p}$ collider, where quark-gluon and antiquark-gluon processes contribute equally. This dominance of quark-gluon initial states, along with the $V-A$ nature of the coupling of the W boson to fermions, implies that at the LHC W bosons with high transverse momenta are expected to exhibit a sizable left-handed polarization [2]. A significant asymmetry in the transverse momentum spectra of the neutrino and charged lepton from subsequent leptonic W decays is therefore expected.

We measure the polarization of the W boson in the helicity frame, where the polar angle (θ^*) of the charged lepton from the decay in the W rest frame is measured with respect to the boson flight direction in the laboratory frame.

The amount of W boson momentum imparted to the charged decay lepton is determined by $\cos\theta^*$, and hence an asymmetry in the $\cos\theta^*$ distribution leads to an asymmetry between the neutrino and charged-lepton momentum spectra. However, because of the inability to determine the momentum of the neutrino along the beam axis, it is not possible to precisely determine the W boson rest frame. To overcome this, a variable that exhibits a strong correlation with $\cos\theta^*$ is introduced. The lepton projection variable, L_P, is defined as the projection of the scaled transverse momentum of the charged lepton onto the normalized transverse momentum of the parent W boson: $L_P = [\vec{P}_T(\ell)\cdot\vec{P}_T(W)]/|\vec{P}_T(W)|^2$. In this expression, $\vec{P}_T(W)$ is estimated from the vectorial sum of

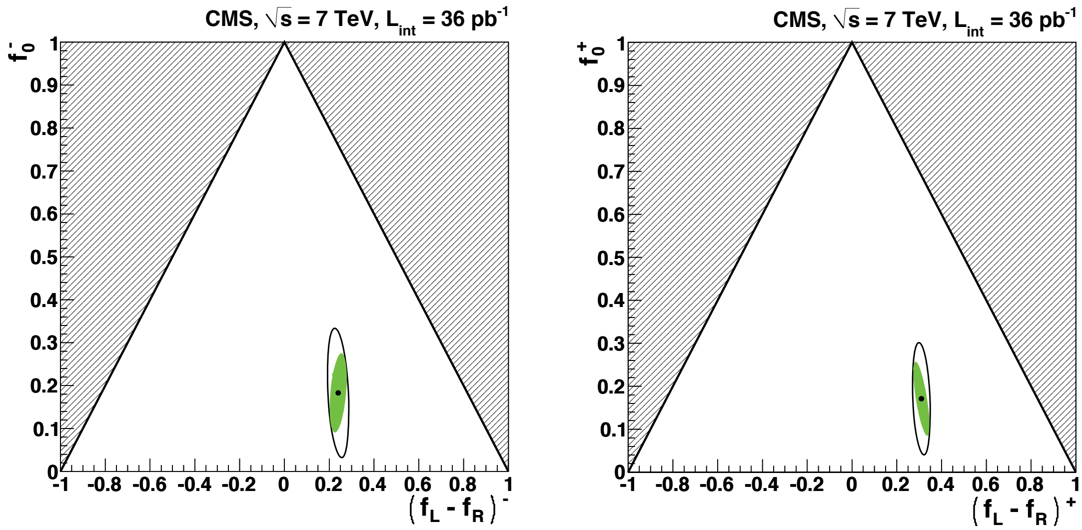

Figure 2: The muon fit result (black dot) in the $((f_L - f_R), f_0)$ plane for negatively charged (left) and positively charged (right) leptons. The 68% confidence level contours for the statistical and total uncertainties are shown by the green shaded region and the black contour respectively. The disallowed region is hatched.

the missing transverse energy and $\vec{P}_T(\ell)$ in the event. In the limit of very high $P_T(W)$, L_P lies within the range [0,1] and $\cos\theta^* = 2(L_P - \frac{1}{2})$.

The left-handed, right-handed and longitudinal polarization fractions (f_L, f_R, f_0) of W bosons with transverse momenta larger than 50 GeV are determined using decays to both electrons and muons. The polarization fraction parameters $(f_L - f_R)$ and f_0 are measured using a binned maximum likelihood fit to the L_P variable, separately for W^+ and W^- bosons in the electron and muon final states. The L_P distribution for each of the three polarization states of the W boson is extracted from Monte Carlo samples which are reweighted to the angular distributions expected from each polarization state in the W boson center-of-mass frame. The L_P distributions are simulated in the presence of pile-up events matching the vertex multiplicity distribution observed in data, corresponding to an average of 2.8 reconstructed vertices per event.

Several experimental and theoretical effects are considered as sources of systematic uncertainty. The most significant sources stem from the energy scale and resolution uncertainties of the jets recoiling against the W boson, which enter in the measurement of its transverse momentum.

The muon final state yields the most precise measurement, $(f_L - f_R)^- = 0.240 \pm 0.036\,(\text{stat.}) \pm 0.031\,(\text{syst.})$ and $f_0^- = 0.183 \pm 0.087\,(\text{stat.}) \pm 0.123\,(\text{syst.})$ for negatively charged W bosons, and $(f_L - f_R)^+ = 0.310 \pm 0.036\,(\text{stat.}) \pm 0.017\,(\text{syst.})$ and $f_0^+ = 0.171 \pm 0.085\,(\text{stat.}) \pm 0.099\,(\text{syst.})$ for positively charged W bosons. The muon fit result is shown in the $((f_L - f_R), f_0)$ plane for each W charge in Fig. 2. The 68% confidence level contours for both the statistical and total uncertainties are also shown. With the current sensitivity, the values of $(f_L - f_R)$ and f_0 do not differ significantly for W^+ and W^-. When compared to recent standard model calculations [2] the results agree well.

This measurement establishes a difference between the left-handed and right-handed polarization parameters with a significance of 7.8 standard deviations for W^+ bosons and 5.1 standard deviations for W^- bosons. This is the first observation that high-P_T W bosons produced in pp collisions are predominantly left-handed, as expected in the standard model.

3. Z and W production in association with b-jets and c-jets

The production of a Z boson in association with b-quarks is an important measurement at the LHC, both as a benchmark channel to the production of the Higgs boson in association with b-quarks, and as a Standard Model background to Higgs and new physics searches in final states with leptons and b-jets. In a first analysis of this channel, we observe 65 events in the data for a high-purity based b-tagging selection, and a measured (expected) purity of $83 \pm 10\,\%$ ($77 \pm 4\,\%$) in data (MC) in Z + b events. For the high-purity based b-tagging selection, with b-jet $P_T > 25\,\mathrm{GeV}$ and $|\eta| < 2.1$, the ratio $\frac{\sigma(Z+b)}{\sigma(Z+j)}$ is found [3] to be 0.054 ± 0.016 (0.043 ± 0.005) in the data (NLO theory predictions) for the $Z \to ee$ selection with both electrons $P_T > 25\,\mathrm{GeV}$ and $|\eta| < 2.5$, and 0.046 ± 0.014 (0.047 ± 0.005) for the $Z \to \mu\mu$ selection with both muons $P_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.1$. The ratio $\frac{\sigma(Z+b)}{\sigma(Z+j)}$ is an important input to theorists, since it is related to the b-quark content of the particle distribution functions, and to the treatment of heavy flavour in matrix-element calculations.

The production of a W boson in association with c-quarks is sensitive to the strange quark content of the proton at the electroweak scale. More than 10% of the W + jets events at the LHC, with $P_T^{jet} > 20$ GeV, contain c jets; assuming that strange and anti-strange quarks have approximately equivalent parton distribution functions, then the ratio $R_c^{\pm} \equiv \sigma(W^+\bar{c})/\sigma(W^-c)$ is predicted to be approximately 1.00. Besides the intrinsic interest of probing the strange and anti-strange quark contents of the proton, a precise measurement of the cross section ratio $R_c \equiv \sigma(W+c)/\sigma(W+\mathrm{jets})$ is an important step towards a reduction of parton density function uncertainties entering future measurements at the LHC, for instance, the W mass. Requiring the jets to have $P_T > 20$ GeV and $|\eta| < 2.1$ and the muons from W decays to satisfy $P_T^{\mu} > 25$ GeV and $|\eta^{\mu}| < 2.1$, we obtain:$R_c^{\pm} = 0.92 \pm 0.19$ (stat.) ± 0.04 (syst.) and $R_c = 0.143 \pm 0.015$ (stat.) ± 0.024 (syst.). These results are in agreement with NLO theoretical predictions [4].

References

[1] CMS collab., *Rates of Jets Produced in Association with W and Z Bosons*, CMS-PAS-EWK-10-012, CERN-PH-EP-2011-125, 2011; and references therein

[2] CMS collab., *Measurement of the Polarization of W Bosons with Large Transverse Momenta in W+Jets Events at the LHC*, Phys. Rev. Lett. **107** (2011) 021802; and references therein

[3] CMS collab., *Observation of Z+b, Z $\to$ ee, $\mu\mu$ with CMS at $\sqrt{s} = 7$ TeV*, CMS-PAS-EWK-10-015, 2011; and references therein

[4] CMS collab., *Study of associated charm production in W final states at $\sqrt{s} = 7$ TeV*, CMS-PAS-EWK-11-013, 2011; and references therein

[5] CMS collab., JINST **3** (2008) S08004